

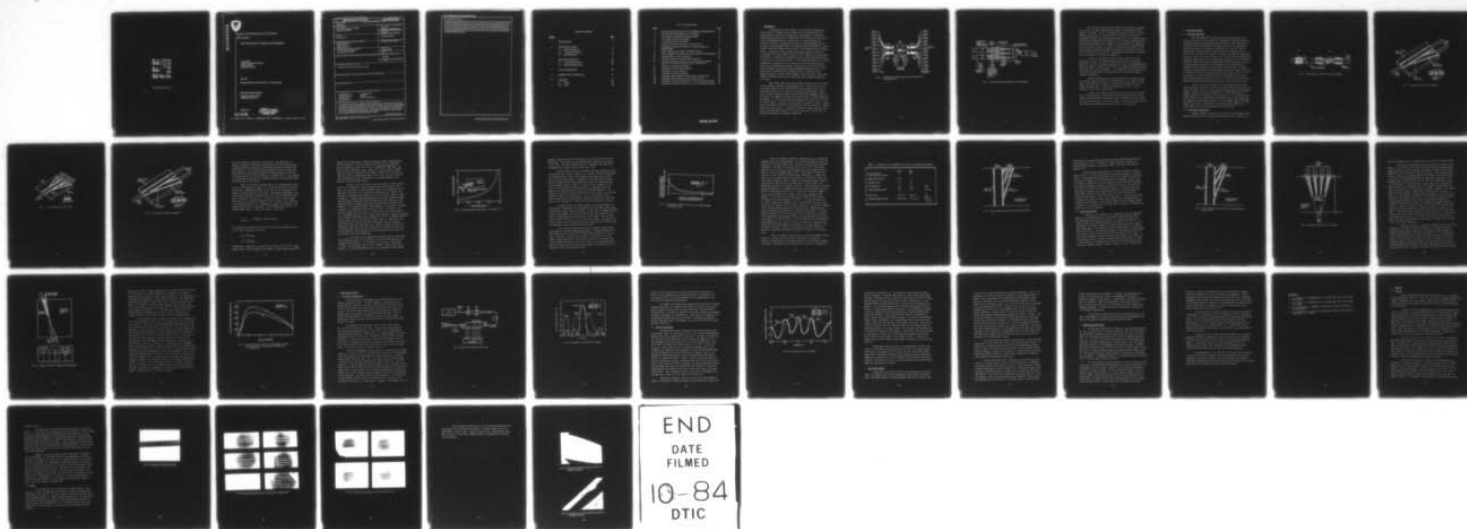
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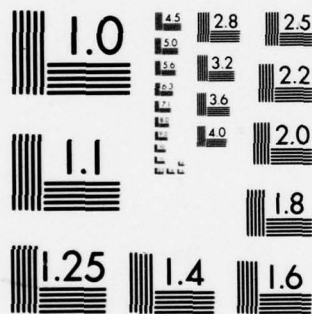
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Research and Development Technical Report

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MULTIPLEXING AND FILTERING OF OPTICAL SIGNALS

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April 1977

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20. ABSTRACT (Continued)

This report covers the work performed during the first six months of this contract, from May through October, 1976. During this period the required work on the multiplexer device was nearly completed, and at this point all but one of the criteria outlined above have been met. Specifically, several devices have throughput losses of 10–15 dB are capable of working with large NA fibers, and have bandwidths of 100 MHz have been constructed. At this time only one requirement has not been fully met; that is, 10 dB signal to crosstalk has been obtained as opposed to 20 dB. However, several new devices, which are near completion, have been designed to improve the results in this area.

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1. INTRODUCTION

The objective of this contract is to develop an optical multiplexing device to combine onto one channel the information carried on several separate fiber optic channels and, subsequently, to perform the demultiplexing operation after transmission over distances of the order of a km. The proposed system is shown in Fig. 1. Twelve transmitting stations use LED's or semiconductor lasers to send asynchronous data at 32 kbits/s over multimode fibers to a centrally located multiplexer station. Figure 2 shows this station in more detail. The information on the twelve fibers is combined by time division multiplexing (sampled at 320 kbit/s per channel) onto three fibers by means of three identical 4:1 multiplexers. In addition, a visible LED is modulated with the timing information, which is also sent on the multimode fibers. At the demultiplexing end, the timing information is separated by color filters, and identical optical devices perform the demultiplexing operation. The main thrust of this contract is the development of the optical multiplexing/demultiplexing device. This device must be compatible with multimode fibers of relatively large numerical aperture, exhibit total throughput losses less than 15 dB, total signal to crosstalk ratio of more than 20 dB, and a bandwidth capability of 1.3 MHz.

This report covers the work performed during the first six months of this contract, from May through October, 1976. During this period we have nearly completed the required work on the multiplexer device, and at this point have met all but one of the criteria outlined above. Specifically, we have constructed several devices which have throughput losses of 10 -15 dB, are capable of working with large NA fibers, and have bandwidths of 100 MHz. At this time only one requirement has not been fully met; that is, 10 dB signal to crosstalk has been obtained as opposed to 20 dB. However, several new devices, which are near completion, have been designed to improve the results in this area. In addition, substantial progress has also been made in the fiber optic aspects of the data link, such as laser/fiber and LED/fiber coupling and fiber/fiber connections.

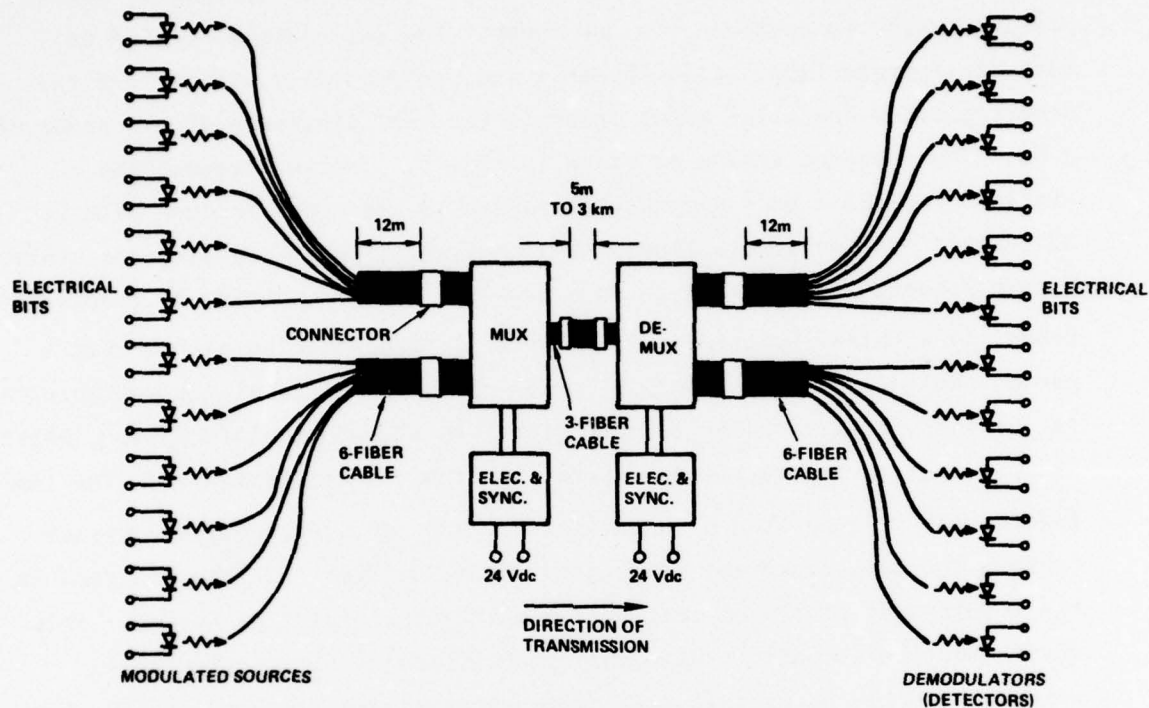


FIG. 1 Complete optical data system for EO multiplexer and demultiplexer link.

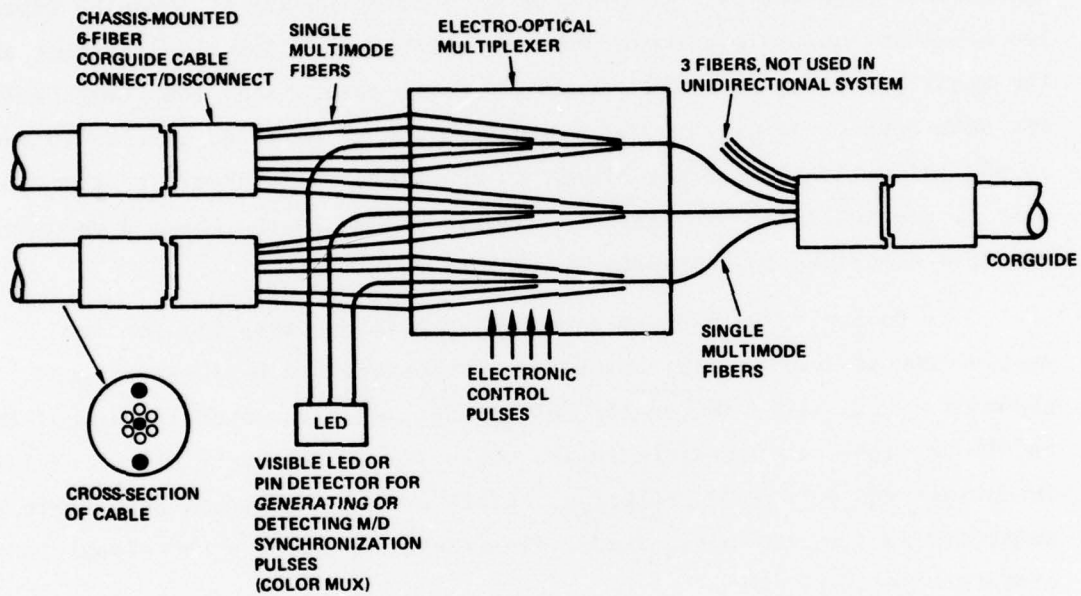


FIG. 2 Fiber connection block diagram for EO multiplexer.

The next four sections of this report will describe the progress made thus far in detail, concentrating mainly on the multiplexer device aspects of the work. In Sec. 2 we explain the general theory of operation of SCRC multimode optical switching devices, including the concept of non-normal incidence butt coupling which allows the use of large NA fibers. Two different multiplexers are described, the 3 dB coupler multiplexer and the spoiler multiplexer, and a summary of the theoretical loss components for both devices is given. The losses are predicted to be between 10 and 15 dB, while the theoretical signal to crosstalk ratio should be limited only by scattering in the crystal. Modifications to the basic 3 dB coupler are also described to increase the isolation.

In Sec. 3 we present the results obtained thus far for the multiplexer devices. (The construction procedure can be found in the appendix.) For the 3 dB coupler multiplexer, we have 15 dB throughput loss and 10 dB signal to crosstalk ratio, while the spoiler multiplexer exhibits 10 dB loss and 8 to 9 dB isolation. It is expected that new designs to be completed in the next month should significantly increase the signal to crosstalk performance.

Section 4 summarizes the results obtained on the aspects of the data link not directly related to the multiplexer device. Laser and LED sources have been used to couple 2.5 mW and 50 μ W, respectively, into a single multimode fiber. A method for constructing a fiber to fiber connector is also under investigation.

In Sec. 5 we summarize the work thus far and describe our plans for the next six months. New devices are to be made with both the 3 dB coupler design and spoiler multiplexer, and a final design will be chosen and constructed within the next three months. Problems in constructing and operating the multiplexed optical data link are not anticipated.

2. MULTIPLEXER THEORY

2.1 Multimode Switching

The SCRC approach¹⁻⁴ to multimode optical switching uses the electro-optic effect in thin wafers of z-cut LiTaO_3 . Efficient switching is made possible by providing a guiding structure to confine and control the optical radiation containing the signal radiation. The appropriate electrode structure is evaporated on both sides of a thin ($50 - 80 \mu\text{m}$) crystal wafer, and the voltage is applied across the thickness of the crystal so as to produce an increase or decrease in refractive index depending on the sign of the applied voltage. In Fig. 3 we show two methods for producing a light guide: in 3(a) a voltage is applied so as to increase the refractive index n and light is guided between the electrode pair; in 3(b) a voltage applied to two pairs of electrodes produces a decrease in n between each electrode pair on either side of the light path. We have chosen the latter method for one multiplexer design for a number of reasons: 1) "barrier" guides do not suffer from electrode absorption loss; 2) the light does not travel in the high electric field region of the crystal, thus limiting possible photoelectric effects; 3) light that is outside the guide can be prevented from entering the guide, thus limiting crosstalk.

In Fig. 4 the basic structure of a 3 dB coupler created using barrier guides is illustrated. With the voltage removed from the gate electrode, the light is free to divide between the main channel and the branch channel. However, the actual percentage of the light which enters the branch depends on the geometry of the intersection, i.e., the angle of the branch relative to the main channel, the angular range of the input light, the length of the interaction region, etc. For example, using a $\pm 2^\circ$ light cone in the crystal, a simplified ray tracing procedure shows that a 1° branch angle will tap off approximately 50% of the light.

2.2 3 dB Coupler Multiplexer

Figure 5 shows the layout for the original 4:1 multiplexer design, which will be called the 3 dB coupler multiplexer, since it consists of

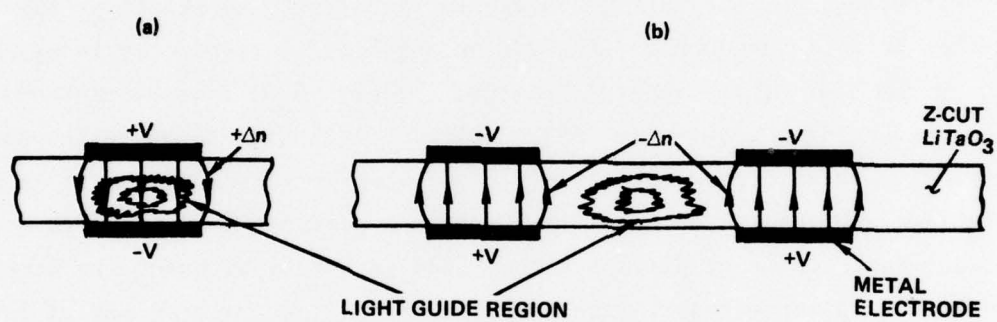


FIG. 3 Two methods for producing an optical waveguide.

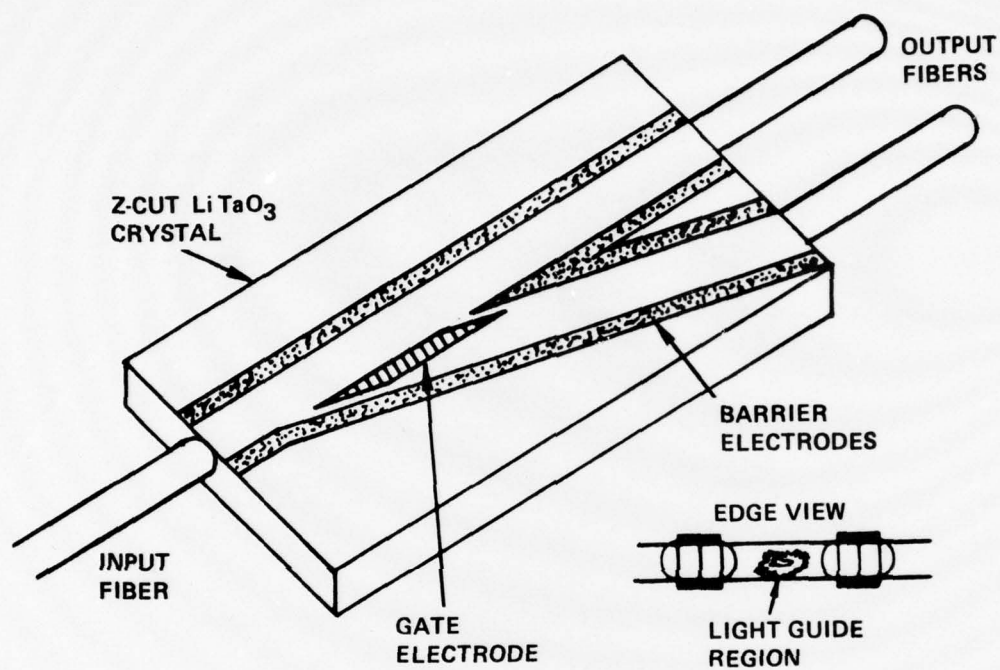


FIG. 4 3 dB coupler using barrier waveguides.

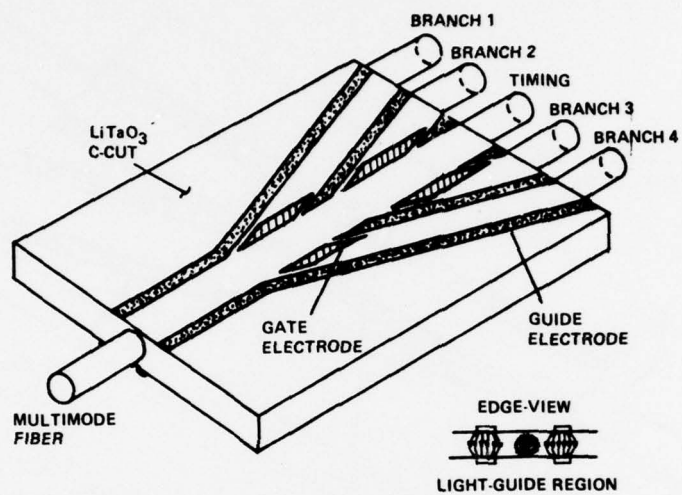


FIG. 5 4:1 multiplexer using 3 dB couplers.

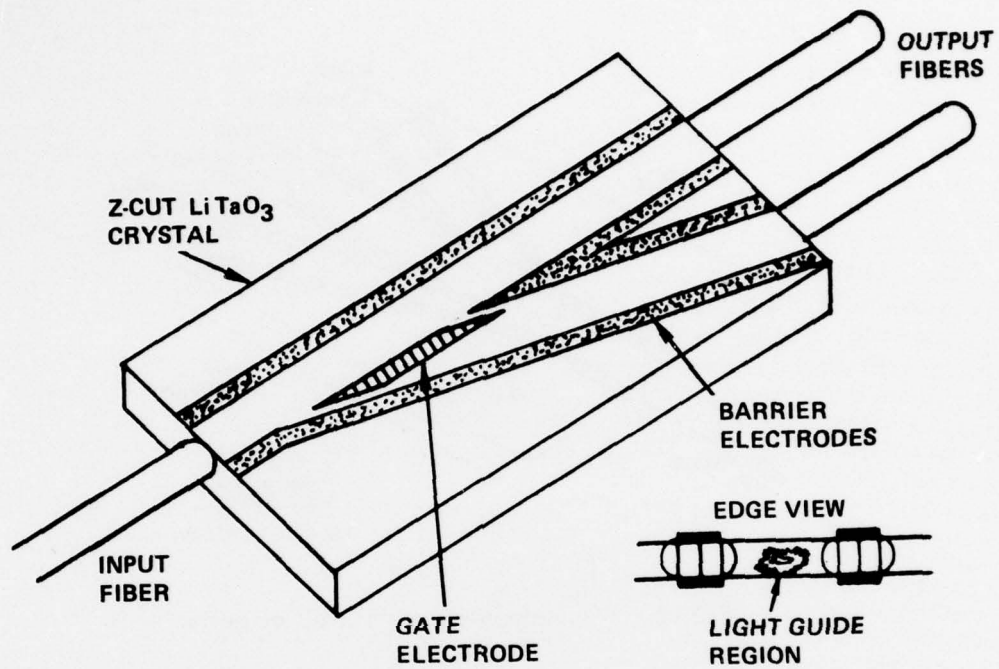


FIG. 4 3 dB coupler using barrier waveguides.

four such couplers incorporated on one crystal. The appropriate dc voltage is applied to the guide electrodes, while the time division multiplexing operation is performed by sequentially removing the voltage from the four gates. The reciprocity theorem guarantees that the device will work equally well with light traveling in either direction, so that the same device may be used for multiplexing or demultiplexing. Fiber coupling is accomplished by directly butt coupling the fibers to the polished input and output ends of the crystal.

While the procedure described thus far is straightforward, modifications are necessary in order to use a large NA fiber with an electro-optic device. Approximately 400 V is the limit to the voltage which can safely be applied across a 50 μm crystal. The maximum angle guided by the electro-optic induced index change can be found from the following derivation. From Snell's law, $n_1 \sin \theta_1 = n_2 \sin \theta_2$, the law for total internal reflection (tir) is found by setting $\theta_2 = 90^\circ$, or $\sin \theta_1 = n_2/n_1$, where θ_1 is the smallest angle for tir. Measuring the angle from the plane of the interface yields $\cos \theta = n_2/n_1$ where θ is the largest angle for tir. For grazing angles $\cos \theta \approx 1 - \theta^2/2$, and using $n_2 = n_1 - \Delta n$ gives

$$\theta_{\text{max, tir}} = \sqrt{(2\Delta n/n)} \approx \sqrt{\Delta n} \quad \text{for LiTaO}_3.$$

For LiTaO₃ with an applied field in the z direction, the change in index in the z and x directions is given by

$$\Delta n_z = \frac{1}{2} n_z^3 r_{33} E_z$$

$$\Delta n_x = \frac{1}{2} n_x^3 r_{13} E_z,$$

respectively. Using the r_{33} coefficient for LiTaO₃ (3×10^{-11} m/V), 400 V applied across a 50 μm thickness will produce an index change of about 10^{-3}

and will guide TM polarized light with an angular range of approximately $\pm 2^\circ$ in the crystal. For the TE modes we must use the r_{13} coefficient which is about 1/4 of r_{33} . Due to the Δn dependence shown above, r_{13} will be 1/2 as effective as r_{33} , so that $\pm 1^\circ$ of the TE light is trapped. Since the index of refraction of the LiTaO_3 is large (2.2), the actual light cone in air is doubled over that in the crystal, but this cone ($\pm 4^\circ$ in air) corresponds to $\text{NA} = .08$, which is still small compared to the emission of most multimode fibers.

In order to use our devices with a larger NA, the light from the fiber must be collimated. Since collimation will also widen the light beam, it is necessary that the collimation apply in one dimension only (in the plane of the device) or otherwise the thickness of the crystal, and therefore the applied voltage, would have to be increased. While it might be possible to imagine some complicated system of lenses between the small fiber and crystal edge which would accomplish this cone reduction, a much simpler system for collimation has been developed which uses direct butt coupling. This technique employs fibers butted to the crystal at an angle. The amount of collimation can be derived as follows. From Snell's law $n_1 \sin \theta_1 = n_2 \sin \theta_2$ and $n_1 \sin(\theta_1 + \Delta \theta_1) = n_2 \sin(\theta_2 + \Delta \theta_2)$ for a small change in $\Delta \theta_1$. Expanding $\sin(\theta + \Delta \theta) \approx \sin \theta + \Delta \theta \cos \theta$ yields $\Delta \theta_1 / \Delta \theta_2 = (n_2 / n_1)(\cos \theta_2 / \cos \theta_1)$ for the angular collimation factor obtained for a cone $\Delta \theta$ of light incident from an index n_1 onto a material with larger index n_2 . Physically, this collimation arises from the fact that larger angle rays are bent more toward the normal than small angle rays. Figure 6 presents a graph of the collimation factor $\cos \theta_c / \cos \theta_f$ as a function of θ_f , and we see that two-fold collimation can be obtained for an incident angle of 66° , while 75° will produce three-fold collimation.

At the present time, commercially available low loss fibers have an NA limited to about .25. Two typical such fibers which were used are produced by Corning (NA = .18, core diam = 85 μm , loss = 6 dB/km) and ITT (NA = .25, core diam = 50 μm , loss = 8 dB/km). Plastic clad fibers with NA = .3 are being developed, but the core diameter for these fibers

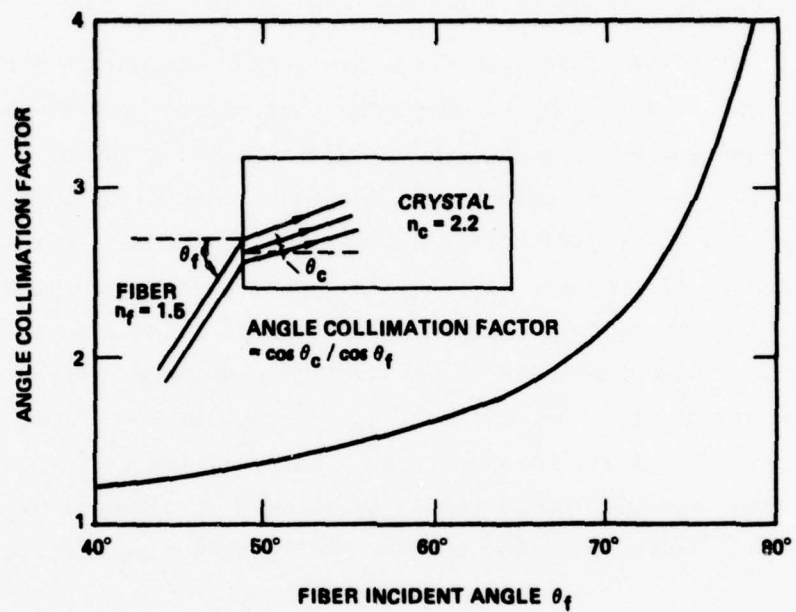


FIG. 6 Collimation factor ($\cos \theta_f / \cos \theta_c$) as a function of θ_f .

generally ranges from 125 to 250 μm which is too large for use with this multiplexer. These fibers may be considered more experimental in nature at this time. Therefore, the multiplexer is designed to use three-fold collimation and a range of fiber NA from .20 to .25.

With the fiber specified, the proper dimensions required for the multiplexer of Fig. 5 may be computed. For example, three-fold collimation of the Corning fiber yields a 255 μm width in the plane of the crystal required for the main channel. In addition, some width must be allowed for the fringing electric field between the electrodes, which penetrates into the channel region. Figure 7 is a plot of the z component of the electric field between two capacitor plates as a function of position along a line midway between the plates for a uniform dielectric. At a distance of one plate separation from the edge of the plates, the field has declined to 20% of its maximum value. Thus, if the crystal is 50 μm thick, about an extra 50 μm should be allowed on either side of the light path for the fringing field, and the total barrier separation is 355 μm .

The angle between the branch channels and the main channel is determined by a compromise, since a smaller angle yields more light tapped off but also a larger interaction length. In our case a 1° angle was chosen. A 355 μm wide channel with 50 μm wide barrier electrodes on either side yields a switch length of 2.25 cm for that branch angle. Thus, the four switches together requires 4.5 cm of the crystal length. The width of the device is quite small (less than .25 cm) and, therefore, the required three 4:1 multiplexers can be fabricated on one crystal.

The 3 dB coupler multiplexer has been designed to work without a polarizer and uses both light polarizations. As mentioned before, the 400 V guide bias will capture $\pm 2^\circ$ of the TM light but only $\pm 1^\circ$ of the TE light. Therefore, included in the design is a long (2.25 cm) initial channel length which allows the TE light of more than 1° to escape from the main channel and fall outside the exit ports. In addition any light which is scattered from the input section toward the output ports will be deflected by the barrier guide structure.

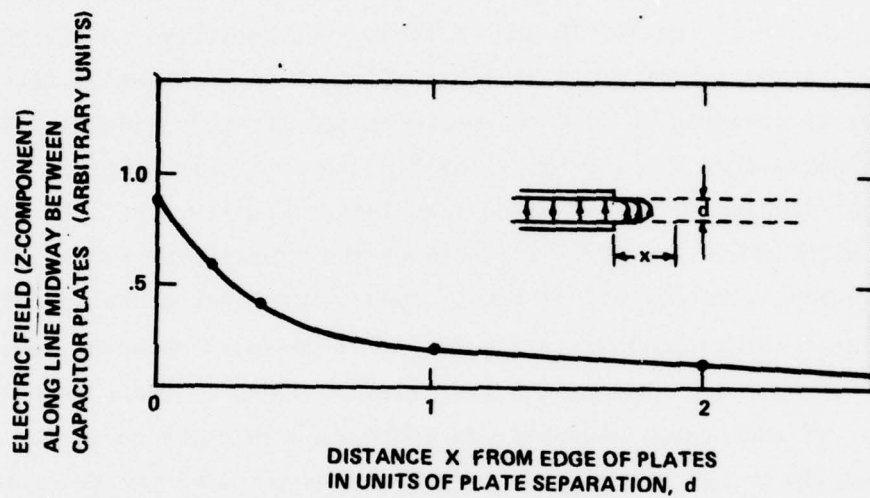


FIG. 7 Z-component of electric field along a line midway between two capacitor plates.

There are a number of different contributions to the theoretical throughput loss for this multiplexer. The reflection losses for TE and TM light are 1 and 4.5 dB, respectively, for both interfaces using three-fold collimation. An index fluid can be used to cut this loss a great deal, since, for $n_f = 1.47$ and $n_c = 2.18$, the optimum index for an antireflection layer is 1.62 at an incident angle of 75° . This reduces the reflection losses to .5 and 2.5 dB for TE and TM light, respectively. Another loss occurs due to the larger angle TE light which is not confined. Also, the light that is captured is free to spread in the fringing electric field to a width greater than the initial channel width, and this light is not recaptured, leading to an estimated 1 dB loss. Finally, there is a size and shape mismatch which is inevitable between the crystal and fiber, and this results in approximately 1.5 dB loss. These losses are shown in Table 1, and the total estimated loss is about 6 dB in going through the main channel. To this loss the switch loss must be added in order to obtain the output of the branch channel. In Table 1, 3 dB and 6 dB switch loss are listed, which can be obtained from a straightforward ray tracing procedure for $\pm 2^\circ$ (TM) and $\pm 1^\circ$ (TE) incident light cone, respectively. However, a more detailed analysis should take into account the fringing electric field distribution, particularly in the branch crotch region. A detailed numerical analysis of this situation has not been completed, but a qualitative argument can be made which leads to the conclusion that there will be an extra 2 or 3 dB switch loss. Thus the total loss for the multiplexer is approximately 13 dB. There is also the possibility of decreasing this switch loss by inserting deflector electrodes in the main channel to tap off more of the light. However, this change would entail complicated electrical connections and would be difficult to fabricate at the present time.

There are a number of variations to the basic multiplexer design of Fig. 5. In Fig. 8 one of the four 3 dB couplers is shown with a "spoiler" electrode added to the branch channel, and electrically connected to the gate. The purpose of this electrode is to increase the signal to

Table 1. Theoretical Loss Components in dB for 3 dB Coupler Multiplexer

	<u>TE</u>	<u>TM</u>	
Reflection Loss (index matching liquid)	.5	2.5	
Unconfined TE Light	3.0	0	
Fringing Field	1.5	1.5	
Size Mismatch	1.5	1.5	<u>AVG.</u>
• MAIN CHANNEL OUTPUT	6.5	5.5	6.0 dB
Switch Loss	6.0 (9.)	3.0 (6.)	<u>AVG.</u>
• BRANCH CHANNEL OUTPUT	12.5 (15.5)	8.5 (11.5)	10.0 dB (13.0)

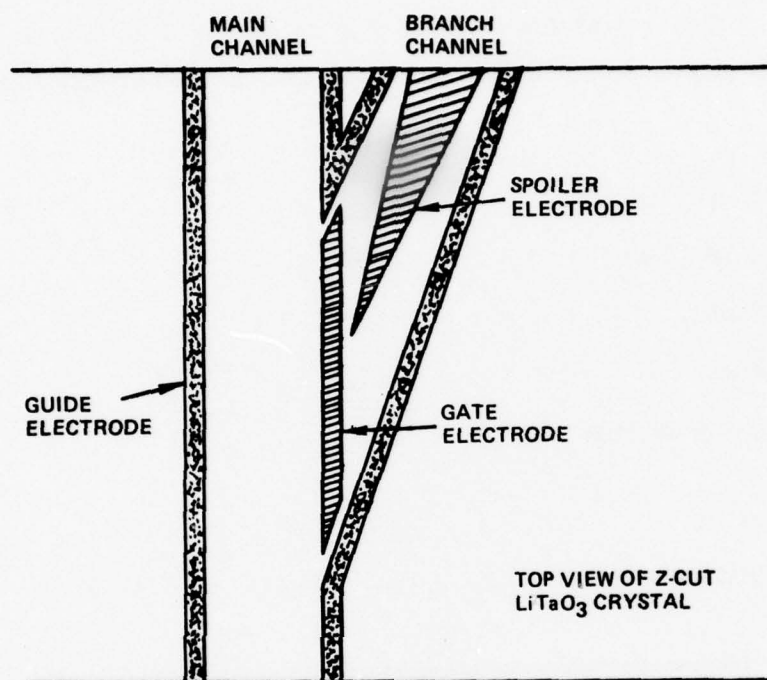


FIG. 8 Barrier waveguide 3 dB coupler with spoiler electrode.

crosstalk ratio by deflecting light which may leak through the gate when the branch channel is "off". In addition a voltage applied to increase the refractive index may help to guide more light to the output fiber when the branch is on.

Another possible improvement of the basic 3 dB coupler design is shown in Fig. 9. In this case the width of the branch channels is tapered. This is a decollimation procedure which increases the light cone angle while shrinking the channel size. The advantage of this approach is that it may be possible to substitute this taper technique for the non-normal incidence butt coupling procedure at least at one end of the device. Also included in this design is a narrow stripe spoiler electrode. It has been found that such narrow electrodes act as excellent deflectors for light traveling at small angles relative to the stripe. This occurs as a result of the refractive index profile under a thin stripe; that is, the profile will have a rounded shape without the flat plateau region that is characteristic of a wide pair of electrodes. Since light is always deflected toward regions of higher n , it is impossible for the light rays to travel in a straight path along a pair of thin electrodes.

2.3 Spoiler Multiplexer

Recently, a new design for a 4:1 multiplexer has been developed which has some advantages over the 3 dB coupler design described above. The new design, which will be referred to as a spoiler multiplexer, is shown (without butt coupling collimation, for simplicity) in Fig. 10. For this device, the light is allowed to spread freely from the butt coupled fiber and impinge on four output ports placed symmetrically at the opposite end of the crystal. A long narrow electrode is positioned in front of each output fiber, so that a decrease in refractive index will block the exit port, while reversing the voltage will help guide light to the output. In this design we accept a minimum 6 dB power division loss, since the power is split among the four output ports, whereas in the 3 dB coupler design there is an inherent minimum 3 dB loss. However, as will be shown later,

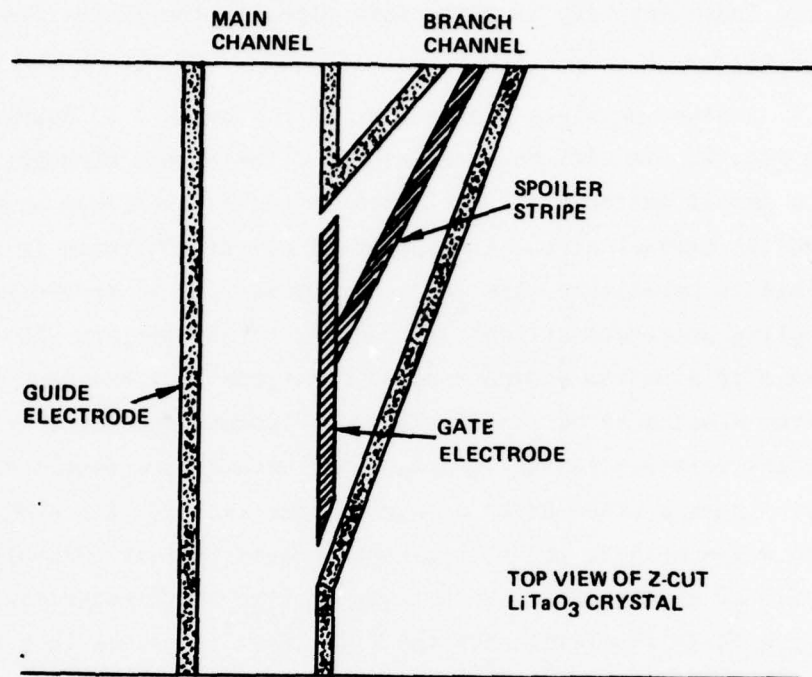


FIG. 9 Barrier waveguide 3 dB coupler with spoiler electrode and tapered output.

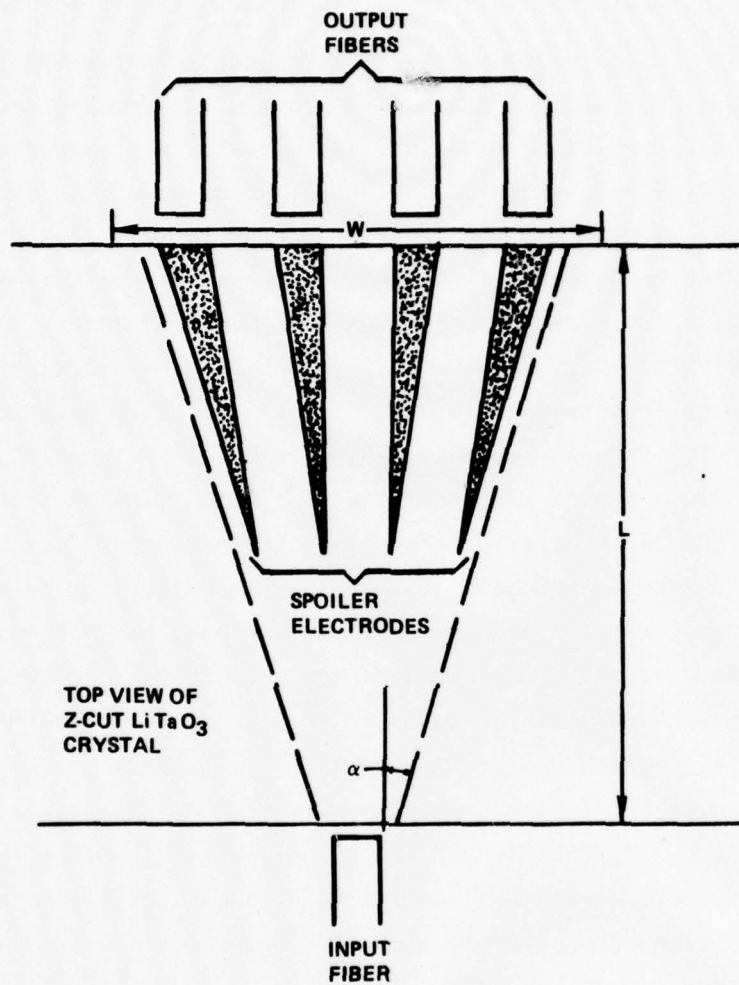
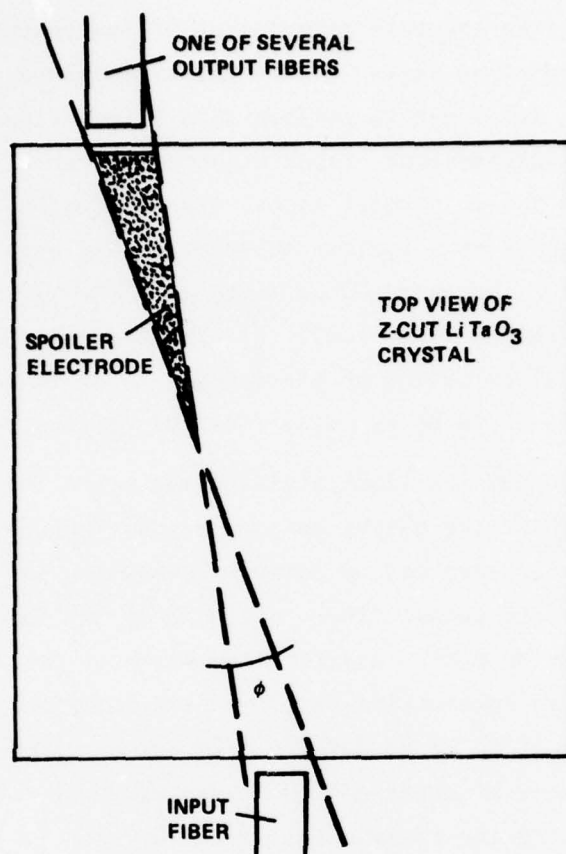


FIG. 10 Electrode design for spoiler multiplexer.

the total throughput loss is actually the same or lower for the new design.

The design procedure will now be outlined for the spoiler multiplexer. First, the size of the fiber core and the desired spacing between output ports (due to fiber cladding, for example) are specified and used to compute W , the overall width of the output section. Next, the fiber NA is used to calculate α , the maximum angle in the crystal, the crystal length L is fixed by the requirement that the cone angle fully illuminate W . The maximum angular range of light ϕ (Fig. 11) that can travel from the input to the output port is then computed. If this range is less than about 1° then the design is satisfactory, since 1° is about the largest angle that can be deflected for the TE polarization in LiTaO_3 . However, if the maximum range of incident angles is larger than 1° then L must be increased. In order to do this without also increasing the throughput loss, the effective fiber NA is decreased by collimation. The procedure is repeated until an acceptably small angular range is found. One possible procedure for designing the deflector electrodes is the geometric procedure illustrated in Fig. 11. With this design no light ray can travel from the input to an output port without encountering a spoiler electrode at an angle of less than 1° . For an $85 \mu\text{m}$ core diam fiber with $125 \mu\text{m}$ OD, such a design calculation yields $L=1 \text{ cm}$ for $\text{NA}=.08$ and no collimation, $L=2 \text{ cm}$ for $\text{NA}=.17$ and two-fold collimation, and $L=3 \text{ cm}$ for $\text{NA}=.25$ and three-fold collimation. Thus, this device, using three-fold collimation, is about one-half as long as the 3 dB coupler multiplexer.

In order to calculate the expected throughput loss for the spoiler multiplexer, the light intensity distribution at the output end of the crystal must be known as a function of the fiber and device parameters. There are several factors that must be considered: (1) The circular cone of the fiber in free space is compressed in one dimension by the LiTaO_3 wafer; (2) The fiber has a non-zero width; that is, light cannot be considered to emanate from a point source; (3) Rays entering the crystal at different angles have different reflection coefficients; (4) The collimation procedure tends to collimate the higher angle rays more than the lower



$d_{\text{core}} = 85 \mu\text{m}$		$d_{\text{fiber}} = 125 \mu\text{m}$
L (cm)	NA	COLLIMATION
1	.08	NONE
2	.17	2:1
3	.25	3:1

FIG. 11 Geometric procedure for designing spoiler electrodes.

angle rays. Thus an accurate calculation of the output cone in the crystal of a fiber butted at an angle becomes fairly involved, and a computer program has been developed to perform this calculation. The following are adjustable input parameters: fiber diameter, fiber NA, fiber index, anti-reflection fluid index, crystal index, crystal length, and desired collimation. The results of a typical calculation are given in Fig. 12 for 3.5 cm long LiTaO_3 , using an 85 μm fiber with $\text{NA} = .25$, three-fold collimation and an AR fluid with $n = 1.62$. As can be seen from the graph, the light intensity distribution at the output end of the crystal is not uniform, and this is to be expected from the factors mentioned above.

The non-uniform light distribution means that the throughput loss will depend on where the output ports are positioned and will be different for each port. The loss can be found by computing the light power in the area occupied by the output fiber, dividing by the total input power, and adding one to two dB extra loss for size mismatch of the fiber and crystal. For the three-fold collimation case, we find that the total theoretical loss ranges from 11 to 13 dB for the four output fibers. If the roles of the inner and outer branches of the multiplexer are reversed for the demultiplexer, then the maximum loss will decrease to the average of the best and worst case loss, or about 12 dB. Furthermore, this throughput does not include any increase in light intensity obtained by increasing the index under the spoiler so as to guide the light. This will yield at least another one or two dB improvement, so that 10 dB throughput loss is a very reasonable expectation for this device. The losses for the spoiler multiplexer are roughly equal to or less than the 3 dB coupler multiplexer for a number of reasons: the new design uses all of the light of both polarizations, it does not use guided light so there is no fringe field loss, and the "3 dB" couplers in the original design tap off less than 50% of the light. However, the throughput loss does increase directly with the number of output ports for the spoiler multiplexer.

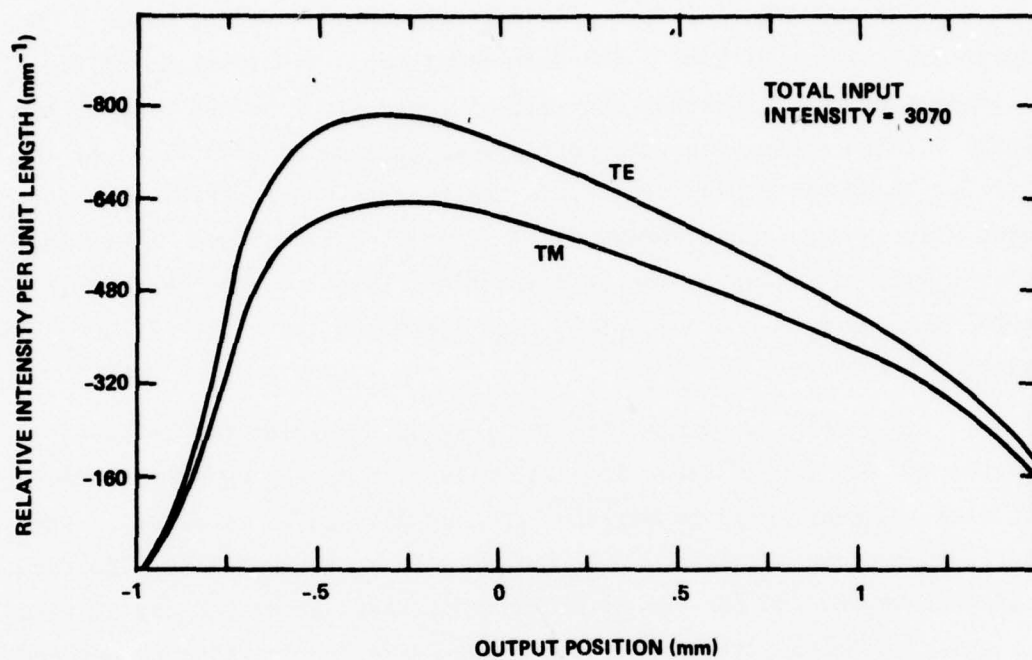


FIG. 12 Light output at end of 3.5 cm Li Ta O_3 crystal for $85 \mu\text{m}$ core fiber with $\text{NA} = .25$, three-fold collimation and $n = 1.62$ AR fluid.

3. MULTIPLEXER RESULTS

3.1 3 dB Coupler Multiplexer

The construction (see appendix) and testing of the basic 3 dB coupler multiplexer of Fig. 5 has been completed. Two versions of the multiplexer were fabricated: one with a ground plane on one side of the crystal and the other using the multiplexer pattern on both faces of the crystal. The devices were similar in their performance except that the ground plane device should be used with a smaller core fiber. This is because the penetration of the fringing field into the main channel is doubled when using the ground plane, and therefore the width of the device channels is reduced.

Two fibers were used for the testing: Corning (85 μm core, $\text{NA} = .18$) and ITT (50 μm core, $\text{NA} = .25$). In each case a He-Ne laser was used with two microscope objectives, 10 \times and 45 \times , so as to overfill the specified NA of both fibers. This resulted in a measured NA of .20 for the Corning fiber and .25 for the ITT. The input and output lengths of fiber were about .5 m long with three-fold collimation terminations on one end. The values of throughput loss, which were measured, are defined as the ratio of the power out of the input fiber divided by the power out of the output fiber. The experimental setup is shown in Fig. 13.

The basic performance of the multiplexer is presented in the graph in Fig. 14. In this case the .25 NA fiber was used with the 4:1 multiplexer. +300 V was applied to the guide electrodes while the gates were switched between +300 V (off) and -100 V (on). The output fiber was scanned along the output end of the crystal with one gate open for each run. From the graph we see that the output of the main channel is about 7 dB down from the input level. This is one dB more than the theoretical analysis predicts and might be due to imperfections such as slight misalignment of the fiber and crystal, or our loss estimates for the fringing field and size mismatch may be too optimistic. The output from the branch channels is 7 to 9 dB below the main channel intensity, which is considerably more than the 4.5 dB predicted by a simple ray tracing analysis. However, as mentioned in Sec. 2,

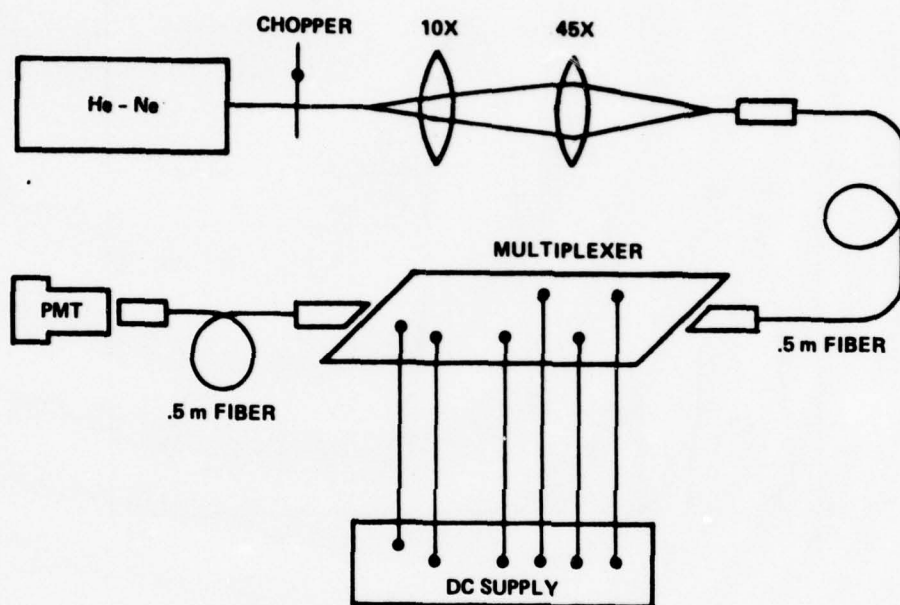


FIG. 13 Schematic of experimental test setup.

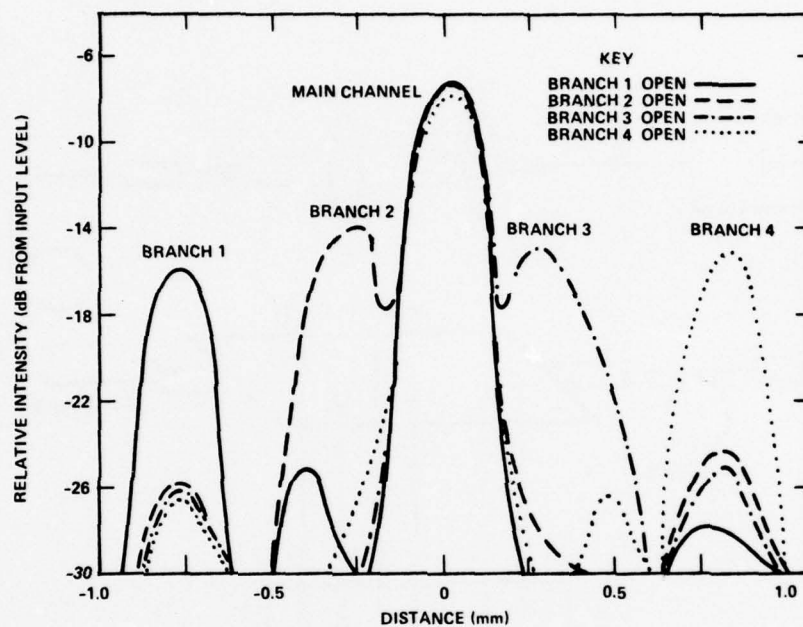


FIG. 14 Performance of 3 dB coupler multiplexer.

it was felt that a more precise analysis which takes into account the effects of the fringing electric field would predict an additional 2 or 3 dB switching loss. The total throughput loss is approximately 15 dB, which meets the minimum ECOM requirement.

The signal to crosstalk ratio, defined as the output of the branch channel with the gate "on" divided by the gate "off" output, can be read from the graph and in all cases is larger than 10 dB. The two devices described in Sec. 2.1 which use spoilers in the branch channels are designed to increase the signal to crosstalk ratio. Both devices are completed, but thorough measurements have not yet been made. Preliminary measurements indicate some improvement in performance, on the order of three or four dB increased isolation.

3.2 Spoiler Multiplexer

One preliminary spoiler multiplexer has now been completed and measurements taken. For this device (2 cm \times 1 cm), two-fold collimation, a Corning fiber, and an input NA of .20 were used. The other test conditions were the same as described above, and the results are shown in Fig. 15. The throughput losses ranged from 8 to 12 dB for an average loss of less than 10 dB. The signal to crosstalk ratio is 8 to 9 dB. In this case, we hope to greatly improve upon the isolation measurements with a new design not yet completed. This is because the device described above does not have the proper ratio of electrode width to spacing. Since it was planned for two-fold collimation, the electrode width was made equal to 170 μm (2 \times Corning clad diam). However, an 80 μm crystal was used and, with this thickness of LiTaO_3 , the fringing fields of the electrodes overlap to a great extent and tend to "wash out" the actual electrode structure. The new design uses three-fold collimation which increases the electrode spacing and also has narrower electrodes to take into account the fringe field effects. This is expected to produce the same low throughput loss, but much better results for the signal to crosstalk ratio.

Theoretical estimates, which do not take into account imperfections in the crystal or random scattering, predict much better results for

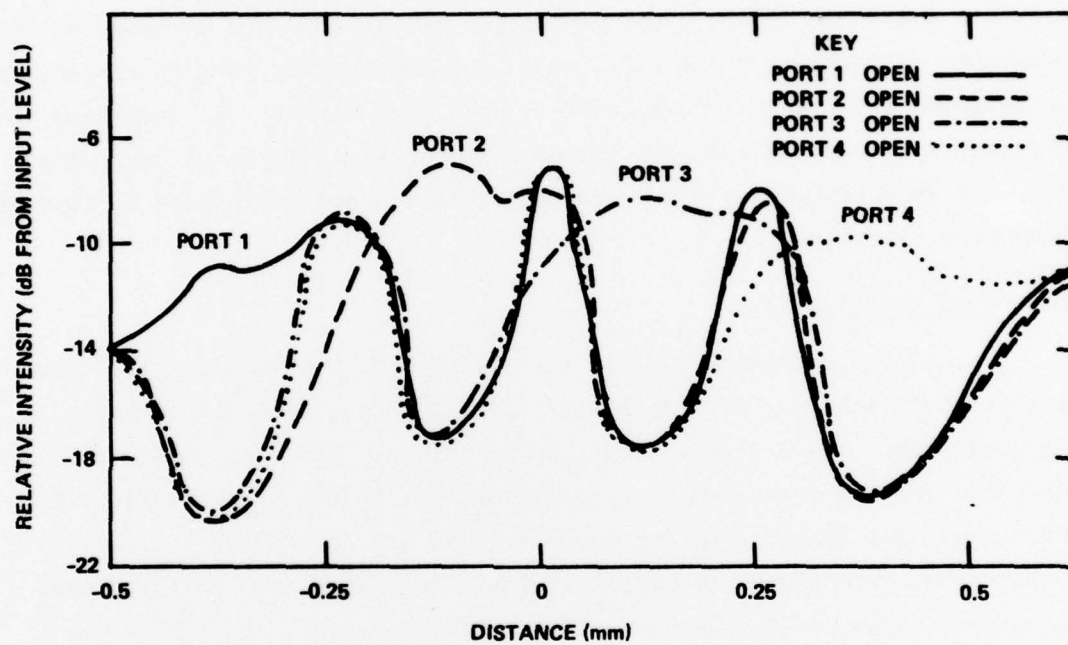


FIG. 15 Performance of spoiler multiplexer.

the signal to crosstalk ratio. In an effort to see whether our results could be improved, a device was fabricated on a small optical grade sample of LiTaO_3 . The higher quality crystal can only be made one to two cm long, greatly limiting the type of devices that could be constructed. It was decided to make a simple barrier guide, as used in the 3 dB coupler multiplexer, on a 1.25 cm long sample and to check the light leakage from the channel. In addition, the fabrication procedure (see appendix) was modified so that the completed crystal was completely free from any bonding agent except for two dabs of silver paint used for electrical connections at points removed from the barrier guide regions. The results of measurements showed a small improvement in the leakage problem over a previously made similar device, but the difference in performance was small. This does not confirm or deny the idea that scattering centers in the crystal cause the observed crosstalk, but it does indicate that the steps described above are not sufficient to deal with the problem. In addition, those steps could not be taken with the longer (3 to 6 cm) multiplexer crystals since optical grade crystal is not available in the required length. In addition, at present such a crystal cannot be made without the support of a crystal bond material.

Measurements were also made of the capacitance of the gate electrodes for the various devices constructed thus far. The results ranged from 10 pF for the simplest gate to 80 pF for the spoiler gate electrode. Using a 50Ω termination this would yield a bandwidth range of about 80 to 600 MHz for a single device or 25 to 200 MHz for three devices operated in parallel. Thus any of the devices is easily capable of meeting the present bandwidth requirements of 1.28 MHz.

4. DATA LINK PROGRESS

While most of the effort thus far has concentrated on the multiplexer development, work is also proceeding on other aspects of the data link. One important area is coupling adequate power into the single fiber

at the source so that the multiplexer can operate adequately. This is not considered to be a prime area for new research in this contract effort. A number of other researchers have developed new source geometries whose emitting pattern will result in improved coupling of sources to single fibers, such as the Burrus diodes. It is not the intention of this program to perform research in this area. However, there is still much to be accomplished in selecting the best commercial LED or laser for optimum optical coupling to a single, small core fiber and finding a means for rigidly and conveniently mechanically coupling the fiber to a device. Thus far we have achieved the best results for LED coupling with a high power (20 mW) diode from Hitachi (HLD-20). By removing the lens cap from this LED and carefully placing the fiber next to but not touching the emitting area, only 50 μ W could be coupled into a single Corning fiber. This may or may not be adequate power for the link depending on the total actual losses encountered in the multiplexer, demultiplexer and other fiber connections. More power may be coupled into the fiber with diodes that are much more expensive or not commercially available.

A more than sufficient amount of optical power, 2.5 mW, has been coupled into a single fiber using a CW laser from Laser Diode (LCW-5). For this device, a micro-positioner device has been developed which rigidly holds the fiber .25 mm from the emitting surface and also allows translational adjustments to optimize the coupling. A thermoelectric cooler will be mounted around the diode to prevent thermal runaway for the 50% duty cycle encountered in Manchester coded data.

Another development which is important for the data link demonstration is a simple means for fiber to fiber connections. A permanent splicing operation is not desirable, since it is more desirable to produce a separate multiplexer unit with attached fiber connectors or fiber stubs, such that external fibers may be plugged into or removed from the device conveniently. Such direct fiber connections with single small core fibers are difficult, but a promising method has been developed. First a clean and perpendicular end on the fiber is produced using a scribe and break

machine constructed for this purpose. A straight and continuous 50 μm groove is then scribed into a piece of plexiglass, and one fiber is permanently epoxied in this groove. A second fiber is attached to another piece of plexiglass. When the second fiber is fitted onto the first piece and slips into the groove, the two pieces are fasted together by a clamping arrangement. Initial test results of this groove concept give 1.2 dB average coupling loss.

The multiplexer electronics are also under construction at this time. Other aspects of the data link construction will proceed after the final 12:3 multiplexer and demultiplexer have been finished.

5. SUMMARY AND FUTURE PLANS

Several optical multiplexer devices have been constructed during the first six months of this contract. Basically, there are two distinct designs which are candidates for the final device to be used in the data link: the 3 dB coupler multiplexer (Fig. 5) and the spoiler multiplexer (Fig. 10). The first devices have been constructed for each design, and both work with large NA fibers and at high data rates. The 3 dB coupler multiplexer exhibits 15 dB throughput loss and 10 dB signal to crosstalk ratio while the spoiler device has 10 dB loss and 8 to 9 dB signal to crosstalk ratio. Second generation designs are planned for both devices which will have improved isolation, while probably not affecting the throughput loss measurement. A reasonable estimate of the improved signal to crosstalk ratio is about 15 dB for either new design.

The final decision on which design to use in the fiber optic link should await the construction and testing of the new devices which will be accomplished in the next month. However, at this point some advantages appear for the spoiler design. The most important advantage is that the required length is much shorter, less than one-half as long as the 3 dB coupler design. This means lower cost for the crystals and much easier fabrication. The construction is also simpler because of the less complicated electrode design. In particular, the 3 dB coupler with spoiler

deflectors is harder to fabricate because of the difficulty in making electrical connections to the gate electrodes (see appendix). Finally, measurements indicate that the spoiler design will have about 5 dB lower throughput loss, or 10 dB less loss for two such devices in the data link. It thus seems clear that, unless the second generation 3 dB coupler multiplexer exhibits better performance in signal to crosstalk ratio, the spoiler design will be the final choice.

As mentioned above, the first priority in the next six months of the program is to construct and test the final version of the multiplexer device. Thus far only 4:1 multiplexers have been constructed, but the new masks for the second generation devices of each type will use 12:3 multiplexing; i.e., three identical patterns have been designed side by side for fabrication on a single crystal. It is expected that in the following two or three months both the 12:3 multiplexer and demultiplexer will be constructed.

Concurrent with the device construction program, the problem of permanent fiber/device coupling will also be addressed. Major problems in this area are not foreseen since coupling is routinely performed now. However, a method will be found for rigidly holding the fibers in a packaged device, using either a permanent potting compound or rigid mechanical holders which allow for some positioning adjustments.

The other aspects of the work on the data link, such as selection of sources, source/fiber coupling, and fiber connectors, have all been completed or are nearly finished. We do not anticipate any problems in successfully completing and operating the optical data link with the present SCRC devices and satisfying the overall ECOM requirements.

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6. APPENDIX

6.1 Devices

Device construction begins with the selection of a z-cut LiTaO_3 wafer of appropriate size, $2 - 7 \text{ cm} \times 1 \text{ cm} \times 50 - 80 \text{ }\mu\text{m}$, purchased commercially (Crystal Technology, Inc., for example). The crystal is selected acoustic grade (no obvious optical flaws), has both faces polished, and arrives waxed on a glass slide.

The first step is the fabrication of the electrode pattern on one side of the crystal. The crystal while mounted on the glass slide is cleaned using a sequence of rinsing steps including acetone, a glass cleaning solution, and distilled water, with ultrasonic cleaning used if necessary. The slide and crystal are coated with Shipley AZ positive resist and spun at 2000 r/min. The pattern is then exposed, developed and placed in the evaporator. If metal absorption may be a problem for the particular device under construction, a very thin layer of Cr is evaporated (10 to 20 Å), followed by a thicker layer (500 to 1000 Å) of Au. After evaporation, the photoresist is lifted off with acetone, leaving the desired metal pattern.

The next step is to turn over the crystal in order to fabricate an electrode pattern on the other side. This is done using a sliding operation: the glass slide, crystal and wax are heated to about 150°C , turned over, and placed face down on another heated glass slide with glycolphthalate coated on the surface. The original glass slide is slid off the crystal in such a manner as to leave the crystal with the electrode pattern down on the new glass slide. The same photoresist procedure described above is now used to create a similar electrode pattern on the top surface.

The crystal top surface is covered with glycolphthalate and mounted for cutting on a diamond saw. The crystal edge is cut at a precise angle relative to the multiplexer pattern, and this angle depends on the degree of collimation desired. For zero collimation, the angle is 0° ; two-fold collimation requires 38° ; three-fold collimation uses 41° . After sawing, the crystal edge is polished using 600 grit, $12 \text{ }\mu\text{m}$, and then $3 \text{ }\mu\text{m}$ paper, followed by $.3 \text{ }\mu\text{m}$ alumina. A photograph of a finished polished edge

is shown in Fig. A1.

The final step is to make electrical connections to the gates or spoilers. In most cases the photoresist mask can be designed so that the leads for the electrical connections are brought out to the side of the crystal. Photographs taken of sections of the actual masks for the 3 dB coupler multiplexer and spoiler multiplexer are shown in Figs. A2 and A3, and some of the electrical connections can be seen there. Cotton swabs with acetone are used to produce holes in the glycolphthalate for these connections. For the bottom side of the crystal, there are cut-outs in the glass slide under the electrical connection pads.

However, for the 3 dB coupler design with spoiler electrodes in the branch channels, the electrode pattern is too complicated to allow the contacts to be brought out to the side. For these crystals, it was necessary to develop a procedure for contacting the narrow gate electrode from above. After creating the pattern on the top surface, a very thick coating of photoresist is applied and allowed to dry. Small holes, 70 to 80 μm diam, are exposed and developed in the resist at the gates using a microscope. The resist is then baked at about 120°C for several hours for hardening, and this layer is left on permanently as an insulator. A path of silver epoxy is created over the photoresist for each connection, and electrical contact is made to the gates through the exposed hole.

6.2 Fibers

Our standard method for terminating a sheathed fiber at right angles is to epoxy the fiber and the sheathing to a brass ferrule which has an opening of about 500 μm . The fiber is then polished using 600 grit paper and the standard sequence of alumina polishing suspensions. For other applications where a ferrule is not needed, a simple scribe and break machine is used to create a clean perpendicular end. This device holds a fiber under tension over a curved surface, and the fiber breaks cleanly when lightly scribed.



FIG. A1 Photograph of polished crystal edge.

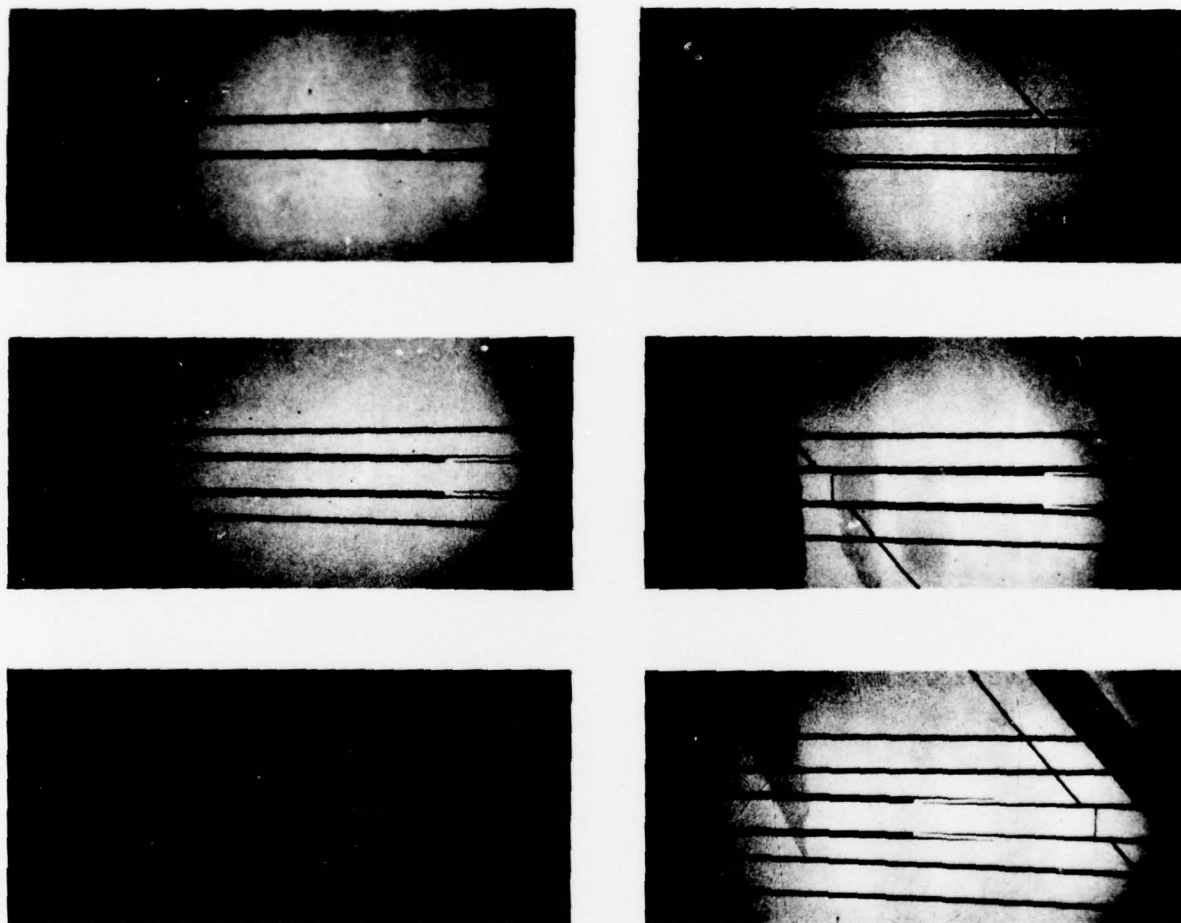


FIG. A2 Photograph showing segments of 3 dB coupler multiplexer mask.

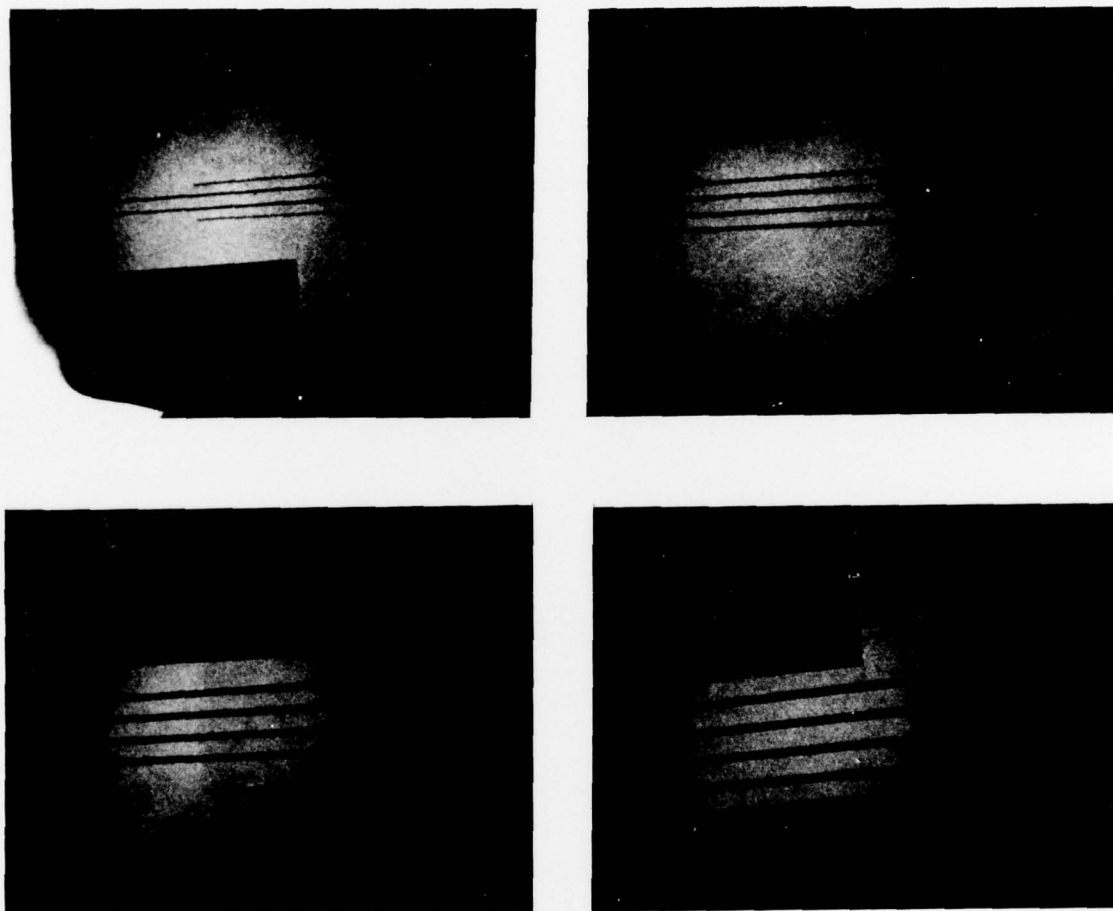


FIG. A3 Photograph showing segments of spoiler multiplexer mask.

For the angular terminations, we use the same procedure described above except that the ferrules are placed in a special angular holder for polishing at a precise angle. Figures A4 and A5 show a single Corning fiber and a portion of a five fiber termination cut at an angle of 75° for three-fold collimation.



FIG. A4 Photograph of single Corning fiber cut at 75° for three-fold collimation.

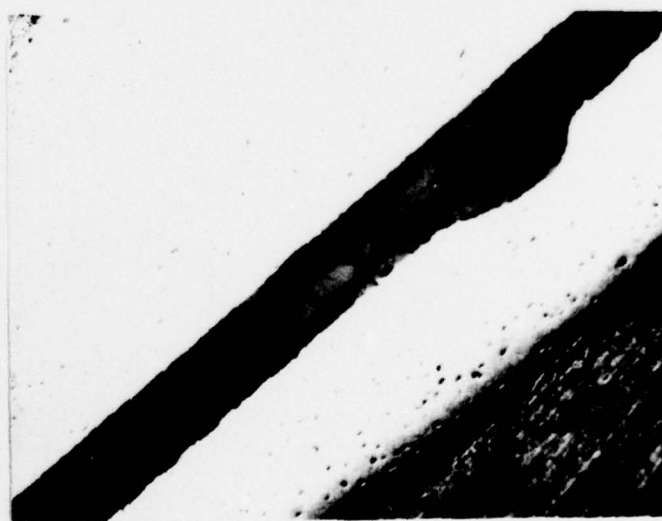


FIG. A5 Photograph of five fiber termination cut at 75° for three-fold collimation.